High-energy astrophysics with VERITAS

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UT Austin, 24-Jan-2011
Outline

• Very high-energy (VHE) gamma-ray astrophysics
• Ground-based observations with Cherenkov arrays
• VERITAS & Instrument performance
• Recent science results
  – Extragalactic sources: AGN, Starburst Galaxy
  – Galactic sources: binary systems, SNR
  – Astroparticle physics: dark matter searches
• Upgrade & Outlook
• Conclusions
Very high-energy gamma-ray astrophysics

- At $E > 50$ GeV, several classes of sources known...

  - Galactic:
    - Supernova Remnants
    - Pulsar Wind Nebulae
    - Binary systems
  - Extragalactic:
    - Active Galactic Nuclei
    - Starburst galaxies

  - ...or expected:
    - Gamma-Ray Bursts
    - Dark matter annihilation
Connection to (astro) particle physics

- Instrumentation and techniques
- Origin of cosmic rays
  - Where are the accelerators?
  - How do they work? To what energies?
    (relevant to Auger, HiRes, etc)
- Understanding the nature of particle accelerators
  - What is being accelerated? (electrons, protons?)
    (relevant to IceCube, Antares, etc)
- Astrophysical sources for fundamental physics
  - Eg. can use AGN flares to look for effects of quantum gravity if start times are well understood
- Discovery space for new physics
  - Eg. Large mass reach for WIMPs
VHE gamma-ray sources

- Crab (nebula) is most constant source in sky; Flux (E > 1 Tev) ~ 2 x 10^{-7} \gamma/m^2/s
- All sources have power law (E^{-\gamma}) spectra to >multi TeV
- Multi TeV \gamma \rightarrow source populations (p, e) at higher energy
  - What is the source population?
  - How do they get accelerated to these energies?
- Dominant production processes believed to be:
  - Inverse Compton scattering (of lower energy photon population)
  - \pi^0 production & decay
- Multi-wavelength, multi-particle studies to disentangle production issues
- Fundamental particle physics issues:
  - Dark matter annihilation?
  - Primordial black holes?
  - Energy-dependent c?
Ground-based observations

- Now on third generation instruments using the Air Cherenkov technique pioneered by Whipple

- VERITAS uses the *imaging technique*: shower is imaged in multi-PMT camera at focus of telescope

- Image analysis allows good angular and energy resolution

- Effective area ~ size of light pool ~ $10^5$ m$^2$
Cherenkov telescopes come full circle over 45 years...
Ground-based observations - arrays

- Imaging arrays (multiple views of same shower) dramatically improve resolution & sensitivity
- Angular resolution $<< 1^\circ$ possible
- Energy resolution $\sim 15\%$

Multiple views allow reconstruction of gamma-ray origin
VERITAS

- An array of four 12-m imaging air Cherenkov telescopes
- Sited at Whipple Observatory basecamp (1300 m a.s.l.) near Tucson, Az
- International collaboration: US, Canadian, UK, Irish groups; ~ 80 collaborators at 20 institutions
- Science observations started in 2006; fully operational since 2007

- 80 GeV to 50 TeV energy range
- Currently most sensitive VHE gamma array in the world
VERITAS - site

- 800 hrs/yr dark time
- 200 hrs/yr partial moonlight
- Summer shutdown (monsoon)

Fred Lawrence Whipple Observatory (FLWO) basecamp

T3, 2006
T4, 2007
T1, >2009
T1, 2006-2009
T2, 2006
VERITAS - site

- Move of T1 led to ~15% increase in sensitivity
VERITAS – telescopes & cameras

- Each 12-m f/1 telescope: tesselated mirror, 350 facets; total mirror area 109 m²
- Each camera: 499 29mm PMTs
- Each PMT: 0.15° f.o.v. (2.6 mrad); overall f.o.v = 3.5°

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Partially assembled camera
VERITAS – electronics

• 3-level trigger:
  – constant fraction discriminator on each PMT
  – telescope pattern trigger requires adjacent pixels
  – multi-telescope (array) coincidence

• Each PMT read out by 500 MSample/s FADC (2 ns sampling)

• Typical event rate: 300 Hz (10% deadtime)
Instrument Performance

- ‘Effective area’ of array ~ $10^5$ m$^2$

4-telescope event; core position outside array
Instrument Performance

• Performance achieved:
  
  PSF: ~0.06° – 0.10°
  pointing accuracy: few arc-minutes (depends on location in camera)
  sensitivity: 50 mCrab @ 5σ in under one hour
  energy resolution: ~15%
  core reconstruction: <25 m out to 180m from array centre
  spectral reconstruction above ~150 GeV

• Crab (standard candle) data used to measure pointing, sensitivity
Instrument Performance

PSF: \(~0.06^\circ - 0.10^\circ\)

Angle between $\gamma$-arrival direction and known source position

3-telescope Crab data
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funky shape from “wobble” data – source offset from centre of field-of-view
Instrument Performance

pointing accuracy: few arc-minutes (depends on location in camera)

multiple Crab runs

circle = 0.05°
Recent VERITAS Science Results

- 33 source detections in 7 source classes:
  - blazars, radio galaxy, starburst galaxy, PWN, SNR, XRB, UnID
Recent VERITAS Science Results

• 16 discoveries:
  – 7 AGN, 3 SNR/PWN, 1 starburst galaxy, 5 other
Extragalactic observations

- AGNs are most common TeV source type
- Aim: understand jet production by supermassive black holes and the physics behind gamma-ray production
  - leptonic?
  - hadronic?
- Multiwavelength campaigns important
- One goal: measure the extragalactic background light (EBL) through its effect on blazar spectra
  \[ \gamma_{\text{TeV}} \gamma_{\text{EBL}} \rightarrow e^+e^- \]
# Extragalactic: AGN discoveries

<table>
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<tr>
<th>AGN</th>
<th>Details</th>
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| **RBS 0413** | - ~5.5σ in 25 h  
- 1.6% Crab  
- X-ray bright HBL @ z=0.19  
- brightest LAT extrapolation  
- ATEL #2272 with Fermi |
| **RX J0648.7+1516** | - ~5.2σ in 18 h  
- 2% Crab  
- Keck: Blazar  
- z=0.179 (Lick 3m)  
- ATEL #2486 |
| **VER J0521+211 (RGB J0521.8+2112)** | - ~4% Crab  
- z=? (unsuccessful MMT, MDM, IR efforts)  
- bright flare (>20% Crab)  
- ATELs #2260 & #2309 |
| **1ES 0414+009** | - ~7σ in 45 h; 2% Crab  
- among X-ray brightest HBL  
- z=0.287  
- EBL! high-z Mkn 421  
- H.E.S.S. detection |
| **1ES 0502+675** | - ~12σ in 30 h  
- 5% Crab  
- z≠0.341? (1h MMT exposure – no features, no redshift)  
- ATEL #2301 |
| **1ES 1440+122** | - ~5.2σ in 50 h  
- <1% Crab  
- hard-spectrum IBL (LAT)  
- z=0.162  
- ATEL #2786 |
Extragalactic: PKS 1424+240

- IBL/HBL
- unknown redshift
- Detected by Fermi-LAT (100 MeV–300 GeV)
- First VHE source discovered as a LAT follow-up
- Discovery triggered observations at other wavelengths


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Extragalactic: PKS 1424+240

- Fermi power law: $\Gamma = 1.73 \pm 0.07_{\text{stat}} \pm 0.05_{\text{sys}}$
- Steep VERITAS power law: $\Gamma = 3.8 \pm 0.5_{\text{stat}} \pm 0.3_{\text{sys}}$
- $z < 0.66$, else EBL would make spectrum softer still
- Flux at \(~5\% of Crab value

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Extragalactic: 1ES1218+30.4

• 1ES1218+30.4:
  – Active Galactic Nucleus, Blazar Class
  – X-ray bright; EGRET source; detected by MAGIC at VHE
  – z=0.182
  – Hard intrinsic spectrum given this relatively large redshift

• Flare Jan 25 – Feb 5, 2009: 7% Crab to 20% Crab
  – ~1 day variability time scale challenges kiloparsec jet model of hard-spectrum emission (Boettcher et al. 2008)
Extragalactic: 1ES1218+30.4

• 1ES1218+30.4:

\[
\frac{dN}{dE} \propto \left( \frac{E}{0.5 \text{ TeV}} \right)^{-3.07 \pm 0.09_{\text{stat}}}
\]

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Extragalactic: Stacked AGN observations

• 2007–2009
  – Exposures on 80% of good X-ray sel. candidates
  – Non-detections: 5σ “stacked” excess (49 AGN, ~6 h each)
  – Most upper limits are best ever: ~2% Crab

• 2009–2010
  – Exposures on 21 Fermi-LAT motivated candidates
  – Upper limits in preparation
  – Will be compared to extrapolated Fermi-LAT flux

Preliminary
Extragalactic: Starburst Galaxy M82

• First observation of VHE gamma rays from a starburst galaxy (SG)

• VERITAS result establishes starburst galaxies as a new class of VHE source

• Starburst galaxies have high rates of star birth and death:
  • many supernovae and stellar winds
  • copious cosmic-ray production
  • gamma-ray production from CR collisions

Nature 472 770-772 (2009)
Extragalactic: Starburst Galaxy M82

• 140 h over 2 years to detect; 5 sigma (post trials) for E > 700 GeV; 0.9% Crab

• Detection supports idea of SNRs as source of cosmic rays
Galactic observations

• Several galactic source types:
  – Supernova remnants (SNR)
  – Pulsar wind nebula (PWN)
  – Binary systems

• VERITAS has extensive targeted observations as well as a Sky Survey of the Cygnus region
Galactic: LSI +61 303

- LSI +61 303:
  - high-mass X-ray binary (period: 26.5 days)
  - massive Be star with compact companion (NS, BH) in tight orbit, and circumstellar disk
  - variable (phase-dependent) emission seen at all wavelengths
Galactic: LSI +61 303

- At least two models for VHE emission in system:
  - relativistic jet powered by accretion (“microquasar”)
  - acceleration in collision of relativistic pulsar wind with companion wind
  - in both models, VHE $\gamma$ emission believed to be inverse Compton
Galactic: LSI +61 303

- Initial observations during 5 orbital cycles:
  - 2-telescope data: Sep – Dec ’06: 32 hours
  - 3-telescope data: Jan – Feb ’07: 12 hours
- VERITAS clearly observed variable emission @ 8.8σ raw rates, binned vs binary phase

Because period is close to lunar period, no data in [0.95, 0.20]
Galactic: LSI +61 303

- emission observed near apastron (phase 0.73): flux > 0.10 Crab
- flux < 0.03 Crab outside in other observed phase bins
- 26.5 day period has 99.94% probability
Galactic: LSI +61 303

- Newer data: less clear to interpret!
- 55 hours of data since Fermi launch, Sept 2008 – early 2010

2008/2009: 37 h of data, 3.4σ overall

2009/2010: 18 h of data, 0.8σ overall

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Galactic: Cassiopeia A (Cas A)

• young (~300 year) supernova remnant
• no (apparent) interactions with nearby material

• VERITAS: 22 hours of data in 07-08 season, 8.3σ
• consistent with point source, at ~3.5% of Crab flux
• modeling uses Fermi-LAT and VERITAS data:
  – prefers hadronic models, but electronic models can be made to work too
Galactic: Tycho (G120.1+1.4)

- supernova remnant discovered by Tycho Brahe (1572)
- X-rays (blue data) indicate electrons up to 10 TeV
- VERITAS: 67 hours of data (2008, 2010), $5\sigma$, ~1% Crab
- Peak significance close to where molecular cloud is interacting with SNR
**Astroparticle: Dark Matter Searches**

- Dark matter \(\sim 25\%\) of energy density of Universe
- Must be non-baryonic, cold, heavy, gravitationally bound
- WIMPs (eg. neutralino) in 50 GeV – 10 TeV range are well-motivated candidates
- Self-annihilation could lead to GeV/TeV gamma signal
- Cherenkov arrays well-suited for this search
Astroparticle: Dark Matter Searches

- Good targets are nearby galaxies with high mass-to-light ratios:
- Local group: M32, M23
- Dwarf Sphericals: Ursa Minor, Draco, Willman I, Bootes I, Coma Berenices
- Globular Clusters: M5

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Astroparticle: Dark Matter Searches

- Dwarf Sphericals are probably best: high mass-to-light ratio (DM dominated), close-by

- Low astrophysical background

  eg: Ursa Minor
  ~20 hrs data
  No detection
  95% CL u.l. @ 1-2% Crab Nebula flux


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Astroparticle: Dark Matter Searches

• Need significant astrophysical boost factor to constrain models
The future: VERITAS Upgrades

• PMT replacement with high efficiency PMTs (summer 2012, funded)
  – Super-bialkali: ~50% increase in QE over current tubes
  – lower energy threshold (trigger threshold from 120 → 80 GeV)
  – improved sensitivity

• FPGA-based Trigger upgrade (installed, now commissioning)
  – lower energy threshold and improved CR event rejection

• Improved atmospheric monitoring with LIDAR System (2011, funded)

• Drive update (study phase)
  – shorter response time to GRBs, etc.
VERITAS Upgrade

QE and PDE measurement of Hamamatsu R9800 by WashU and UCSC

Simulation of gamma-ray response
Outlook

• Typical year is 800-1000 hours of observing
• First two years: Four Key Science Projects (50% of time)
  – Dark matter, AGN, SNR, Sky Survey
• Remainder of time: competitive observations (40%) decided by TAC (time allocation committee), and discretionary (10%)
• Now: observing by competitive proposals (TAC), typically oversubscribed by ~2x
• Upgrade will improve sensitivity; moonlight running will increase duty cycle
• Likely > 4-5 years of stable operation ahead of us
Conclusions

- Four-telescope VERITAS array is now in full operation
- Most sensitive Cherenkov array in the world
- A healthy observing program with many detections & discoveries: galactic, extragalactic, astroparticle, GRB
- Active collaboration with other VHE instruments, Fermi/LAT and instruments at other wavelengths
- Upgrade underway w/several years of stable operation following